Temporary atmospheres produced by human activities on the Moon

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Abstract

Outgassing from materials, whether through the ascent/descent stages of lunar vehicles, airlock depressurizing, rover or astronaut suit outgassing, may cause an effect of unwanted accumulation of volatiles at the surface and exosphere. This is especially important at (or proximal) to permanently shadowed regions (PSRs) at the lunar poles. Herein, we provide estimates of expected outgassing from various human-landed objects on the Moon, including backpacks, airlocks, rovers, landers, trash and mining operations. Astronaut suits produce some level of oxygen outgassing (Helou et al., 2022), which may transport and condense in these PSRs, even in micro- cold traps (Glavin et al., 2010).We estimate the outgassing from drill mining and trash-to-gas conversion assuming a specific technology is operating. These outgassing systems can create local, temporary atmospheres in the vicinity ($\sim$100 km radius) of the sources. The atmosphere may be particularly high within meters of the source. To obtain column densities for these temporary atmospheres, we first bracket ranges for the gas number loss as a function of time. We then derive the maximum distance traveled and the time the released molecules remain in the exosphere for a single ballistic hop, assuming the molecules are ejected from the surface of the object at its surface temperature. In some cases, such as the astronaut backpack and the rover, the temperature is that of the source. Given this information, an average and peak local exospheric density and column density can be estimated. We find that backpacks, airlock releases, and the Starship lander can create relatively high-density local atmospheres, with local near-lander outgassing water densities exceeding $10^7/cm^3$. This local water exosphere is over 10^6 times greater than the LADEE-derived lower limit of the natural water exosphere at $\sim$3/cm^3. Thus, the anthropogenic temporary water exosphere will likely dominate the environment near the lander, making an assessment of the natural exospheric water environment difficult.

1. Introduction

The goal of this study is to estimate the column abundance, composition, and duration of an exosphere produced by human-made systems and human activities on the Moon. In particular, we aim to determine at what point the outgassing from human instruments and structures will produce a collisional atmosphere and whether this atmosphere will be permanent. The transient exospheres described here last fractions of an hour. A permanent atmosphere will survive for the lifetime of the Moon. As defined here, a transient exosphere or atmosphere will not survive longer than a lunation after the source is removed. We examine the likely sources and rates of various gas releases resulting from human activities on the Moon. These sources include outgassing of water from astronauts' backpacks, air released from airlocks during astronaut egress, Starship outgassing, mining activities, trash and rovers. Estimates for the first two are based on data from the Apollo program, with modifications for modern backpacks, and estimates from past and planned

airlocks. The estimates for mining and trash are more difficult to determine, and thus come with larger uncertainties. The exospheres resulting from mining for rare earth elements and for mining of ice will obviously be different. We have only estimated the water loss from mining water ice. In all cases we give minimum and maximum rate estimates. We will compare these estimates to outgassing from the surface water deposits that are formed by the exhaust plume during landing (Prem et al., 2020; Farrell et al., 2022).

One of the most important physical parameters determining the survivability of an exosphere is the sticking coefficient of the atom or molecule on the surface. Adsorption energies are crucial in determining whether a molecule will adhere upon interacting with the surface, and desorption energies are important for determining how long the molecule remains on a surface. Molecular oxygen is a particularly interesting case because it has a relatively low adsorption energy, but we consider that it will adhere to the surface due to rapid chemical reactions. There is no systematic study of sorption properties of lunar regolith for any molecule except water. Dissociative adsorption activation energies measured on metallic Mo_2C (001) (Shi et al., 2016) and desorption activation energy level of CO_2 on mesoporous silica (Teng et al., 2017) may not be appropriate for the granular, complex mineralogy comprising lunar surface.

In order to obtain an estimate of the exospheric and column density of outgassing in the region near the anthropogenic source, we will assume that all degassed molecules will stick on contact with the surface. In other words, the molecules are assumed to make a single hop (one bounce) from their source as was done in Farrell et al. (2022). The porous nature of the regolith increases the liklihood of sticking, as does the space weathered nature of the surface. A small correction equal to 1.67 for the possibility of secondary bounces (Farrell et al., 2022) will not affect the conclusions of this paper.

The sources and their molecular compositions treated in this paper are listed in Table 1. Outgassing from backpacks, mining, rovers, landers, and rocket exhaust include large amounts of water which will affect water-sensing instruments placed on the surface to examine the natural water environment. Airlocks and trash-to-gas conversion systems release molecular oxygen, nitrogen, carbon dioxide, carbon monoxide and hydrocarbons. The examination of outgassing from mining and trash are technology-specific applications: the calculation of outgassing is dependent upon the exact method of mining and trash elimination being applied. We examine a specific technology in each case. In this paper N refers to the column density integrated vertially from the surface of the Moon (cm^{-2}), n refers to the number density in the exosphere (cm^{-3}) and n_0 refers to the number density at the surface of the Moon (cm^{-3}).

2. Atmospheres resulting from various anthropogenic sources

2.1. Backpacks

Astronaut suits produce some level of oxygen outgassing (Helou et al., 2022), which may transport and condense in these PSRs, even in micro- cold traps (Glavin et al., 2010). While on Extra Vehicular Activities (EVA), the astronauts will be cooled in part by a sublimative cooling device that dissipates heat by evaporating water (described in (Metts & Klaus, 2012)). Campbell (2012) describes the AEMU (Advanced Extra-vehicular Maneuvering Unit), which is a proposed suit for use in microgravity as well as Lunar and Martian surfaces. He gives a designed heat dissipation of 1200 BTU/hr (351.69 W) for 8 hrs. Metts & Klaus provide the heat of vaporization (h_{vapor}) of water in a radiator similar to those used to cool space suits to be 677 Watt hour/kg. They also provide the following equation to quantify the mass of water required to remove a given amount of heat:

$$m_{H_2O} = \frac{\int (q_{met} + q_{PLSS})dt}{h_{vapor}} \quad (1)$$

In Eq. (1), q_{met} is the metabolic heat output from the astronaut and q_{PLSS} is the heat output from the life support system. These terms are combined into the 1200 BTU/hr heat output (Campbell, 2012). Eq. (1) can be solved for the outgassing flux of water, $\frac{dm}{dt} = 0.1443$ g/s for one spacesuit or 0.2886 g/s for two suits. We assume a backpack the size of the Apollo backpack, with a surface area of 3.43×10^4 cm^2. Dividing by the total radiator surface area gives an offgassing flux density of 4.207×10^{-6} $g/cm^2/s$.

We examine a planned 4 h EVA and an 8 h EVA. Given that the radius of the molecule's trajectory is far greater than the astronaut's path, the backpack can be considered as a point source. However, since the backpack is vertical, only half of the water molecules are ejected into the upward pointing hemisphere. Thus we will treat the upward directed half and the downward directed half separately.

2.1.1. Water molecules initially ejected into the upward hemisphere

The approximate time a water molecule spends on each bounce is τ_{atm}, is given by

$$\tau = \frac{2v}{g} \quad (2)$$

where v is the initial most probable velocity perpendicular to the surface and g is the surface gravity, 162 cm/s^2.

The initial most probable velocity perpendicular to the surface, based on a Maxwell Boltzmann distribution of energies/velocities, is given by

$$v = \sqrt{\frac{2kT}{m}}cos\theta \quad (3)$$

Table 1
Source Compositions.

Source	Composition (by mass)		Reference
xEMU (Backpack)	100 % H_2O		Metts & Klaus, 2012
Airlock (P_{atm} = 14.7 psia)	23.301 % O_2, 76.699 % N_2		NASA, 2020
Airlock (P_{atm} = 10.2 psia)	29.711 % O_2, 70.289 % N_2		NASA. 2020
Airlock (P_{atm} = 8.2 psia)	37.057 % O_2, 62.943 % N_2		NASA, 2020
Mining	100 % H_2O		Assumed ice mining
Trash	56.7 % CO_2, 6.8 % CO, 36.6 % CH_4		Olson et al., 2021
Outgassing from rover/ spacecraft/lander	H_2O; H_2O+F; H_2O, F, Hydrocarbons**		Fraenz et al., submited; Schlappi et al, 2010., Paterson and Frank, 1989
Rocket Exhaust *	Large CH_4-O_2 Rocket: 45 % H_2O, 55 % CO_2	Large H_2-O_2 Rocket: 97 % H_2O, 3 % H_2 Small Rockets: 32 % H_2O, 30 % N_2, 15 % H_2, 3.6 % CO_2, 13 % CO	Farrell et al., 2024; Lee, 2020 (Small Liquid Rockets)

Rocket exhaust is not modeled in this paper since it has been considered elsewhere.
Outgassing composition is dependent on composition of body, lubricants, other components.

where θ is the mean angle with respect to the normal, and is assumed to be 45°. Assuming a lower limit to the temperature, T=200 K, we obtain v = 3. $\times$ 10^4 cm/s andτ = 370 s. Assuming an upper limit on the backpack temperature of 400 K, v = 4.3 $\times$ 10^4 cm/s andτ = 228 s. We estimate gas flow for ambient, equilibrium with the astronauts, and heated backpack temperatures of 200, 294, and 400 K.

The outgassing rate per cm^2 is multiplied by the area of the backpack to obtain the outgassing rate per unit time. This is multiplied by the time spent in the atmosphere, assuming one bounce, divided by the area into which the gas flows in one bounce time. The total number of water molecules in the region within one bounce of the backpack is then:

$$N_{exo} = \frac{dn}{dt} \tau_{exo} \frac{S}{\pi r^2} \qquad (4)$$

where dn/dt is the degassing rate of the backpack in cm^{-2}-s^{-1}, S is the surface area of the backpack from which the gas emanates (3.43 $\times$ 10^4 cm^2), and r is the radius of the area into which the gas flows in one bounce:

$$r = \frac{2vcos(\theta)vsin(\theta)}{g}, \text{where v is the most probable velocity.} \qquad (5)$$

This becomes $r = \frac{2(vcos(\theta))^2}{g}$ if v is the most probable velocity as defined by a Maxwellian distribution and θ is 45°, thus cos(θ) = 0.707.

At 200 K, the perpendicular velocity is 3 $\times$ 10^4 cm/s, the one bounce time is 370 s, and the radius of a water molecule is approximately 110 km, thus the bounce area is 3.9 $\times$ 10^{14} cm^2. The molecular outgassing rate for the backpacks is that rate that carries off the excess heat from the astronauts' bodies and the heat from the life support system. The total molecular outgassing rate for a 2 person EVA is dn_t/dt = 9.65 $\times$ 10^{21} molecules/s, estimated from *xEMU(Backpack) Initial Mission Offgassing Rates* (Campbell, 2012), but half of this is ejected into the upward-directed hemisphere. Given a hop time of

~370 s, the average column abundance of water from the backpacks, N_{exo}, at 200 K, asuming a single bounce, is

$$N_{exo}(T = 200K) = 1.8 \times 10^{10} cm^{-2} \qquad (6)$$

If the water degasses from the backpack at a modest 70 F (294 K), the perpendicular outgassing velocity is slightly higher, 3.67 $\times$ 10^4 cm/s, the radius is approximately 166 km (assuming a point source), and the hop time is 450 s, thus the area is 8.7 $\times$ 10^{14} cm^2, and the average column abundance of water from the backpacks, N_{exo}, is

$$N_{exo}(T = 294K) = 1. \times 10^{10} cm^{-2}. \qquad (7)$$

For an upper limit to the backpack radiator of 400 K, for which the average perpendicular gas velocity is 4.3 $\times$ 10^4 cm/s, the hop time is 530 s, and the radius is 228 km, and the area into which the gas is deposited is 1.6 $\times$ 10^{15} cm^2. Thus

$$N_{exo}(T = 400K) = 7.3 \times 10^9 cm^{-2} \qquad (8)$$

Since the water sticks to the surface at 200 K, the water exosphere only lasts as long as the EVA, but the water will subsequently degas from the surface as H_2O, H_2 + O, or OH. The water probably accommodates to the surface temperature upon alighting.

The larger area over which the water is deposited at higher temperature results in a reduction of the column abundance by about a factor of 2.5. However any further desorption from the surface beyond the one-bounce assumption applied here will increase these values by a factor of 1.7 (Farrell et al., 2022). Parameters for backpack outgassing are given in Table 2 for three assumed temperatures of the gas, 200 K (ambient) and 294 K (in equilibrium with the astronauts), and 400 K (heated backpack).

The maximum surface water abundance measured by LADEE is ~3 cm^{-3} (Hodges and Farrell, 2022). For a temperature of 294 K, the scale height for H_2O would be ~83 km. The assumption of a Chamberlain exosphere would give an average surface number density of water of < 10^3 cm^{-3}. Estimates of the surface number density of water vary from 13.7 cm^{-3} at the equator to < $1c^{-3}$

Table 2
Parameters for backpack degassing.

Parameters for backpack degassing	Value (200 K)	Value (294 K)	Value (400 K)
Velocity (45°) to surface normal (cm/s)	3.0×10^4	3.67×10^4	4.3×10^4
Radius one-bounce atoms (km)	110	166	228
One bounce time for H_2O (s)	370	450	530
Area of one bounce (cm^2)	3.9×10^{14}	8.7×10^{14}	1.6×10^{15}
Average Column abundance (H_2O) (cm^{-2})	1.8×10^{10}	$1. \times 10^{10}$	$7.3. \times 10^9$

above 80°latitude (Jones et al., 2024). The estimated native column abundance of water, given a scale height of 83 km, is $1. \times 10^7 - 1. \times 10^8$ cm^{-2}. Thus, the temporary, local surface number density from the astronaut's backpacks exceeds the ambient value by two to three orders of magnitude within 100 km of the backpack.

2.1.2. Downward directed molecules from backpacks

In the case of the backpack, consider that half of the flux is directed in the downward hemisphere. The average downward velocity at the surface is

$$vdown = v_0 \cos\theta + gt \tag{9}$$

where the angle, θ, is measured from the downward vertical direction. If the midpoint of the backpack is at L cm above the surface then the time, t, to reach the surface is given by the quadratic equation

$$L = v_0 \tau \cos\theta + \frac{1}{2} g\tau^2 \tag{10}$$

Given L=150 cm, and $v_0 = 0.53$ km/s, the average time for the molecules initially going downward to reach the surface is 0.004 s. Since 15 % of the flux, or 1.4×10^{21} molecules/s, is directed downward, or 0.2 g/s per astronaut, the downward flux in 0.004 s is < 0.001 g. This strikes the surface within ∼150 cm of the astronaut, filling a volume, V, which is more or less a quadrant of a sphere of radius 150 cm, or V=3.5×10^6 cm^3 the exospheric density in this volume is 1.6×10^{12} cm^{-3}. With a surface area of 3.5×10^4 cm^2, resulting in a column of ∼2×10^{14} molecules/cm^2. Thus a local collisional atmosphere may exist within a meter and a half of the astronaut, and follows him/her but does not persist. However, the water molecules that are adsorbed on the surface may dissociate, and react with hydrogen from the solar wind to produce 2·OH and H_2, within fractions of a second. Although the surface number density is high around the astronaut, it would take about 1.6 years to saturate the soil at this rate, even if the astronaut remained stationary and there were no desorption or other surface effects.

2.2. Airlocks

Four different airlock pressures were considered as part of this study, with the minimum airlock volume of four considered by NASA. The first airlock volume was from a 2023 study into lunar habitat access which assumed a volume of 15 m^3 (Stromgren et al., 2023). The next two were

variations of a proposed two-chamber airlock from Johnson Space Center (JSC.) They considered the full airlock (volume = 13.3 m^3) or solely the outer chamber (volume = 5.9 m^3) (Howard, 2021). The last airlock was from a NASA EVA office publication with 8 m^3 as a possible minimum volume (NASA, 2018). Based on these, the minimum possible volume for an airlock was assumed to be 5.9 m^3 and the maximum to be 15 m^3. Estimates for the volume of the lunar space suit were unavailable, so an average volume of the human body of 0.06522 m^3 was used (Nagao, et al., 1995). Based on that volume, and the assumption that 2 astronauts will be in the airlock when it is depressurized, occupied air volumes were calculated for each. Airlock assumptions are given in Table 3.

Modern airlocks use pumps to remove most of the air before opening, reducing the amount of air lost each time the airlock is opened (Trevino & Lafuse, 2008). It is assumed that 90 % of the air in an airlock can be reclaimed (Trevino and Lafuse, 2008; Stromgren et al., 2023). The ideal gas law is used to calculate the mass of the air in the airlock when it is at cabin pressure and then that mass is used to find the air lost each time the airlock is cycled, airlock mass loss, m_{lost}. The human volume is subtracted from the unoccupied volume to calculate the volume of air. Airlock designs differ in the size of the hatch, the air pressure released, and the mix of oxygen and nitrogen gases. An illustrative example is the sample of airlocks presented by Heinicke et al. (2022). Table 4 gives the molecules released per egress and rate of release for four airlock designs assuming a depressurization time of 10 min.

$$m_{lost} = 0.1 \left(\frac{P_{cabin} V_{airlock}}{R_{air} T_{cabin}} \right) \tag{11}$$

The International Space Station (ISS) currently operates with a cabin pressures of 14.7 psia (NASA, 2022). NASA, however, has proposed three possible cabin pressures for a

Table 3
Airlock Assumptions.

	Min
Unoccupied Airlock Volume (m^3)	5.9
Occupancy	2
Human Volume (m^3)	0.06522
% Air Reclaimed	90
T_{atm} (K)	293
R_{air} (psia*m^3/kg/K)	0.04164
P_{atm} (psia)	14.7, 10.2, 8.2

Table 4
Molecules outgassed per egress.

Airlock Pressure	Molecules/egress	dn/dt (molecules/s)
1 STP (1.01 bar) (Apollo)	2.1×10^{25}	3.5×10^{22}
0.35 bar (Quest Airlock)	7.3×10^{24}	1.2×10^{22}
0.10 bar (RECLAIM)	2.08×10^{24}	3.5×10^{21}
6 mb (Safe Mars)	1.25×10^{23}	2.1×10^{20}

lunar habitat: 1 bar (14.7 psia), 0.7 bar (10.2 psia), and 0.56 bar (8.2 psia). Each of these atmospheres would have O_2 saturations (by volume) of 21 %, 27 %, and 34 %, respectively (NASA, 2020). The cabin air is at about 75F (297 K). Thus, values are calculated at the temperature of release and at ambient temperature (Table 5). Proposed airlock pressures are: 1 bar (14.7 psia), 0.35 bar (5.1 psia), 0.1 bar (1.5 psia), and 6 mb (9×10^{-2} psia).

Since the airlock is vertical, 15 % of the molecules are directed downward such that they will strike the surface within 1.5 m of the airlock, with a time to strike the surface less than 1 s (see Section 2.1). These molecules will adsorb onto the surface, where they will most likely become a layer of O_2 and N_2 molecules available to create a secondary exosphere, or will engage in chemical reactions with solar wind protons. We consider the upward directed molecules in Table 6. We have modeled airlocks having surface pressures at release of 1 bar (14.7 psia), 0.35 bar (5.1 psia), 0.1 bar (1.5 psia), and 6 mb (9×10^{-2} psia). The air degassed contains O_2 and N_2 but the fraction of O_2 is different in each case (Table 6). The fraction of O_2 increases as the pressure decreases to maintain the required oxygen for life systems. The lowest two pressures, RECLAIM and Safe Mars, require 100 % oxygen but do not maintain the oxygen levels required for life. However, the astronauts would presumably be breathing air from their backpacks and not from the airlock. The airlock is evacuated within 10 min for the RECLAIM method (Trevino and Lafuse, 2008). The depressurization time for the SafeMars Airlock is 30–40 min, but the rate is exponentially decreasing. The pressure decreases by half within 5 min (Vrankar et al., 2023).

A goal for the Artemis program is to reduce the gas lost from the current 2.39 kg/EVA to 0.24 kg/EVA (Trevino and Lafuse, 2008). This reduction, when realized, will reduce these exosphere column abundances by an order of magnitude.

2.3. Mining

Lunar In-Situ Resource Utilization (ISRU) technology is still rapidly developing, so many significant assumptions had to be made to quantify the outgassing (loss) of a possible lunar mining operation. The first assumption that had to be made was the production demand for different compounds. In the far term, there are a variety of useful compounds that could possibly be mined on the moon; however, the only near-term ISRU use case that seems to be seriously considered is providing oxygen to a settlement. While there are a variety of proposed processes to extract oxygen from lunar regolith, the electrolysis of water extracted from the lunar regolith is assumed for this study due to its perceived likelihood and current advanced understanding (Kornuta et al., 2019). However, as plans for ISRU plants are further developed, this may have to be reassessed. Another method for extracting water is simply vaporizing the regolith.

It is widely assumed that for an initial ISRU plant to sustain a 4 astronaut presence on the Moon, it should be capable of producing 1000 kg/yr of O_2 (Cilliers et al., 2020) with production possibly growing to 10,000 kg/yr during later missions (Sangers and Kleinhenz, 2022). Mass loss during mining is assumed to be between 10 % (Kornuta et al., 2019) and 25 % (Kleinhenz and Paz, 2020). Although there will likely be some losses when converting the water to oxygen, at present, those losses cannot be quantified with any confidence. Thus the conversion of water to oxygen through electrolysis is assumed to conserve mass.

There are a few different options for the extraction of volatiles from lunar regolith, but they can be broadly broken down into drilling and surface heating (Kornuta et al., 2019). A drill seemed to be the most likely method of volatile extraction on early lunar missions due to its compact size. The Honeybee Drill seems to be the most developed and well-studied. It was assumed that a set of 40 drills, each with a diameter of 5 in, were constantly in use (Sanders et al., 2019). By scaling the production scenario presented in Sanders et al. to the assumptions made in this study, esti-

Table 5
Parameters for airlock gas release.

Parameters for Airlock (O_2)	Value (T=200 K)	Value (T=297 K)
Velocity 45° to surface (cm/s)	2.2×10^4	2.7×10^4
Radius of one-bounce atoms (cm)	6.3×10^6	9.33×10^6
One bounce time for O_2 (s)	280	342
Area of one bounce (cm^2)	1.25×10^{14}	2.7×10^{14}
Parameters for Airlock (N_2)	**value (T=200 K)**	**Value (T=297K)**
Velocity 45° from the surface (cm/s)	2.4×10^4	3.0×10^4
Radius of one-bounce atoms (cm)	$7. \times 10^6$	1.0×10^7
One bounce time for N_2 (s)	296	380
Area of one bounce (cm^2)	1.6×10^{14}	4.1×10^{14}

Table 6
Average column abundances resulting from One Airlock Depressurization.

Pressure	%O_2	%N_2	Column Density O_2 (cm^{-2}) T=200 K	Column Density N_2 (cm^{-2}) T=200 K	Column Density O_2 (cm^{-2}) T=297 K	Column Density N_2 (cm^{-2}) T=297 K
14.7 psia (1 STP)	21	79	1.7×10^{10}	$5. \times 10^{10}$	3.5×10^{9}	1.1×10^{10}
10.2 psia (0.69 STP)	27	73	1.5×10^{10}	3.1×10^{10}	3.5×10^{9}	0.7×10^{10}
8.2 psia (0.56 STP)	34	66	1.6×10^{10}	2.4×10^{10}	3.5×10^{9}	0.5×10^{10}
5.1 psia (0.35 STP)	55	45	1.6×10^{10}	1.0×10^{9}	3.5×10^{9}	2.1×10^{9}
1.5 psia (0.10 STP)	100	0	2.6×10^{9}	0	2.0×10^{9}	0
0.088 psia (6 mb)	100	0	1.5×10^{8}	0	1.0×10^{8}	0

Note that the order of magnitude atmosphere is similar for all airlocks considered. For both O_2 and N_2 the exosphere produced from airlock depressurization would be easily detectable by a mass spectrometer.

mates of the minimum and maximum outgassed mass flux densities can be determined (Table 7).

Using the following equations, the amount of water that must be extracted from the lunar regolith given a desired oxygen output can be computed:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{12}$$

The required mass of mined water given the oxygen demand rate, $\dot{m}_{oxygen}$, is given by Eq. (13).

$$\dot{m}_{water}(kg) = \dot{m}_{oxygen}(kg) * \frac{1 kmol O_2}{31.998 kg O_2} * \frac{2 kmol H_2O}{1 kmol O_2}$$
$$* \frac{18.015 kg H_2O}{1 kmol H_2O} \tag{13}$$

Due to power constraints during the lunar night, an initial mission will occur only during the lunar day. Over a year, a mining operation will only be able to operate for 225 earth days (61.64 % uptime) (Kleinhenz and Paz, 2020). Using this assumption, Eq. (13), and the mass loss rates given, the minimum and maximum water loss rate during mining for an initial and sustained mission can be calculated (Table 8).A conservative estimate for water loss due to mining of ice is $1.3 \times 10^{20} - 3.3 \times 10^{21}$ molecules s^{-1}, the lower limit assuming initial mission loss rates at 10 % loss and the upper limit assuming sustained rates at 25 % loss. Given a one bounce model, and an assumed temperature in Shackleton crater of 90 K, the column abundance of H_2O is $4 \times 10^{8} - 1. \times 10^{10}$ cm^{-2} spread over a local area of 7.8×10^{13} cm^2. Changing the water temperature to 200 K results in column abundances of $3 \times 10^{8} - 7.5 \times 10^{9}$ over a

local area of 1.8×10^{14} cm^2. This exosphere is considered transient and will last as long as the mining operation continues. The mining operation is assumed to operate for 225 days per year, and to be shut down for 140 days. If surface heating is the method of extraction, then the water extracted and lost will be at a higher temperature. For drilling, frictional heating will also increase the water temperature. Changing the water temperature from 200 K to 294 K in section 1.1 decreased the column abundance by a factor of 2, assuming the loss rates in Table 8 are unchanged. Since these are order of magnitude estimates, we do not expect the conclusions to be substantially changed.

2.4. Trash

There is very little literature available on the disposal of trash on the Moon, especially during initial missions. It is possible that on the initial 14 day missions the astronauts may take all of their trash with them. There are also proposals to convert the astronauts' trash on sustained missions to rocket fuel for the return trip to Earth, thereby reducing the added gas production to nearly zero (Nur, 2013). There are also proposals to dump the trash in the open, bury it, store it in the empty fuel tanks of old landers, or fill disposable containers and dump those (Howard and Litaker, 2021). None of these options is well studied in the lunar environment. There has been a moderate amount of work towards trash disposal in microgravity for the ISS, Gateway, and possible deep space missions to Mars and

Table 7
Mining Assumptions.

	Min	Max
Resources Produced	O_2 by mining H_2O	
Initial Mission O_2 demand (kg/mission)	38.35 (scaled from 1000 kg/year)	
Initial Mission Productive Mining Days	14 (100 % uptime)	
Sustained Mission O_2 demand (kg/year)	1000	10,000
Initial Mission Degassing rate (g/s)	0.0317	0.317
Sustained Mission Productive Mining Days	225 (61.64 % uptime)	
Mass Loss (wt%)	10	25
Mining Platform	Honeybee Robotics PVEx Drill	
Required Mining Rate (kg/h)	65 (for 1000 kg/year O_2 Production)	650 (for 10000 kg/year O_2 Production)

Table 8
Mining Total Outgassing Rates.

	Min	Max
Initial Mission H_2O loss rate (g/s)	0.003927 (at 10 % loss)	0.09818 (at 25 % loss) 61.64 % uptime
Sustained Mission H_2O loss rate (g/s)	0.03927	0.98178
Column abundance (H_2O) 90 K cm^{-2}	$4. \times 10^8$	$1. \times 10^{10}$
Column abundance (H_2O) 200 K cm^{-2}	$3. \times 10^8$	7.5×10^9

Table 9
Trash-to-gas mass rates for a 4-person crew for 1 year (Olson et al., 2021).

Vented Gas	Mass Vented (kg/year)	Velocity cm/s (perpendicular)	Atm. Lifetime (s)
CO_2	1513	2.4×10^4	306
CO	181	3.0×10^4	365
CH_4	976	3.9×10^4	483
Total	2670		

beyond. While many technologies have been investigated, none of them is very mature, and only small tests of trash disposal technology have been carried out on the ISS. The vast majority of the ISS' trash is still disposed of by packing it in resupply capsules before they are deorbited.

The most promising technology with deep space trash disposal seems to be a 'trash-to-gas' system where, via a variety of processes, solid waste is converted into gas. These technologies have been designed with a microgravity spacecraft in mind, and it is unclear how applicable they will be on the lunar surface. In DRATS (Desert Research and Technology Studies), trash removal was incorporated into rover expeditions, conducted at crew discretion every two to three days (Howard and Litaker, 2021). In this simulation, the EVA crew member will gather wet trash, dry trash, and human waste from their respective receptacles, and place them in the Suit Port Transfer Module (SPTM). The EVA crew member will then remove the SPTM from the suit port and stow it on the rover aft deck until the rover reaches a location where it can be dumped.

NASA has not yet determined how it will dispose of trash permanently. Scientists at Glenn Research Center are studying ways to convert trash to methane gas for rocket propellant (NASA News/Glenn Research Center, Nov. 2013). A four-person crew on a one-year mission would generate 2100 kg of trash in a year (Ewert and Broyan, 2013). A standardized waste model was developed by Nur (2013) to capture the gas for production of methane propulsion. The input to the waste reactor consisted of 16.2 % polyethylene sheet, 21.2 % urine brine, 11.2 % fecal simulant, 8.9 % food waste, and 12 other categories. The waste was heated to 500 C or 600 C. Only CO and CO_2 were recorded. Production of CO_2 is highly temperature dependent; higher rates of CO_2 were produced at 600 K vs. 500 K incinerator temperature. She reported that an operational frequency of 16 h per day for 350 days per year would produce 490 kg CO_2/year. She concluded that the system would need to be scaled by a factor of 4.8 to produce 4000 kg/year of O_2/CH_4 propellant.

Eight trash-to-gas conversion processes were evaluated by Olson et al. (2021). The technology that was used for our study is an *Incineration Gasification* process (Table 9). This technology leaves very little solid waste behind, and it is one of the more mature trash to gas technologies (Olson et al., 2021). It produces 56.7 % CO_2, 6.8 % CO, and 36.6 % CH_4 by mass. Olson, et al. compared a variety of trash to gas processes; the minimum and maximum mass vented rates in Table 10 represent the minimum and maximum off-gassing rates of the various technologies in their paper. We are considering the incineration of trash on the Moon from a four-person crew. We assume that trash will outgas CH_4, CO_2 and CO, and possibly higher order hydrocarbons. The outgassing rates given in Table 10 assume that the gas is not saved for re-use (Olson et al., 2021).

If the CO_2 travels an average of R=75 km/hop the area covered by the CO_2 at 297 K is $\sim 1.8 \times 10^{14}$ cm^2. CH_4 travels about 188 km/hop, into an area of $1. \times 10^{15}$ cm^2, and CO travels about 108 km/hop into an area of 3.7×10^{14} cm^2.

The trash-derived exosphere will disappear at night because of very cold temperatures. These estimates are for a 4-man crew. The gas is assumed to be warm, 297 K, due to cooling as it outgasses from a presumed nozzle. It could be warmer, however.

2.5. Outgassing from rovers and landers

Outgassing from spacecraft have been measured at Rosetta, BepiColombo and MSX. Schläppi et al. (2010) reported degassing from Rosina on the Rosetta spacecraft as a function of time during the mission. The initial 1/e decay time was 30 days, after which the desorption dropped from 3×10^{-9} mb immediately after launch to 6×10^{-11} mb one year later. Afterwards the degassing remained fairly stable, only decaying to 3×10^{-11} mb 7 years later. Initial degassing from Rosina was dominated by water, whereas the long-term outgassing from Rosina was dominated by fluorine, which is probably a decay pro-

Table 10
Outgassing rates and column abundances for trash from a 4-man crew.

	Min Offgassing Rate (molecules/s)	Max Offgassing Rate (molecules/s)	Min.; Max Column (cm^{-2}) stick	n_0 (cm^{-3})
CH_4	1.2×10^{21}	1.8×10^{21}	$6. \times 10^8$; 8.7×10^8	<50
CO_2	3.25×10^{19}	6.6×10^{20}	5.5×10^7; $1. \times 10^9$	<208
CO	1.2×10^{20}	6.7×10^{20}	1.2×10^8; 6.5×10^8	<72

duct of the lubricant, Braycote. The outgassing from ACIS on the Chandra X-ray mission was dominated by carbon (80 %) with only 7 % fluorine (Schläppi et al., 2010). The source of fluorine on the Chandra spacecraft is probably also the Braycote lubricant. On the other hand, degassing measured on BepiColombo during cruise phase, reported by Fraenz et al. (2023), was assumed to be almost entirely water, consistent with initial outgassing from Rosina, although some fluorine cannot be excluded. The outgassing rate from BepiColombo was related to the temperature of the spacecraft components, with considerable short-term variation related to the temperature of various instruments, the antennae, and the heat shield. Outgassing increases when the instruments are on, especially when more than one instrument is turned on at the same time. It is also related to the spacecraft orientation with respect to the Sun, but is not particularly correlated with heliocentric distance. The total flux from BepiColombo varied considerably (Fraenz et al., 2023):

$$1.3 \times 10^5 cm^{-2} s^{-1} < Flux < 1.3 \times 10^9 cm^{-2} s^{-1}.$$

The upper limit is correlated with the temperature of the solar arrays.

2.5.1. Outgassing from rovers

We conclude that outgassing from modern rovers is dominated by water, and may be correlated with the composition of the spacecraft parts, especially lubricants that may be employed, and with the temperature. The temperature will obviously not be in equilibrium with the ambient surroundings, but will increase when spacecraft instruments are turned on. This will be especially true for drills used for core samples and mining, and also for moving parts. Therefore, it is difficult to predict outgassing for the rovers such as VIPER, but when the instruments are turned on it should be expected that outgassing will be near the upper limit measured on BepiColombo. In comparison with expected natural source rates for the lunar exosphere, the minimum outgassing rate is greater than the source rate for either ion sputtering or micrometeoroid vaporization of Na, but in contrast, the rover source is very localized and primarily outgasses water. Given the three-dimensional nature of man-made components, the surface footprint area is much less than the actual area of the instruments, by a factor exceeding 6 (assuming a square box).

The outside surface area of VIPER is 5.7×10^6 cm^2. Multiplying this by 6 to account for the area of the instruments inside, the area is about 3.6×10^7 cm^2. (https://scien-ce.nasa.gov/mission/viper). If we assume that the outgassing from VIPER is water, and the rate is similar to BepiColumbo at $> 10^9$ cm^{-2} s^{-1} (Fraenz et al., 2023) then the outgassing rate is $\sim 4 \times 10^{16}$ molecules s^{-1}. Assuming a temperature of 297 K, a time of flight of 450 s, and a one bounce range of 170 km, the area into which the water molecules migrate in one bounce is 9.1×10^{14} cm^2. The resulting average column abundance of H_2O is $\sim 2 \times 10^4$. A correction of a factor of 1.67 to correct for possible secondary bounces (Farrell et al., 2022) would increase this to $\sim 3 \times 10^4$ cm^{-2}. These water molecules will stick to the surface and eventually desorb as H_2.

A second estimate of outgassing is from the Rosina instrument on Rosetta (Table 11). The degassing rate 20 days after launch was 3×10^{-9} mb, corresponding to a near-spacecraft density of $5 \times 10^7/cm^3$ for their reference temperature of 297 K (Schläppi et al., 2010). The outflux of gas (which is density times outflow velocity near 500 m/s) is then $\sim 2 \times 10^{10}/cm^2$ s^{-1}. Assuming VIPER outgasses at the same flux, and has a rover area of 3.6×10^7 cm^2, the overall outgassing rate would then be $dn/dt \sim 7 \times 10^{17}/s$. This corresponds to a column abundance of 6×10^5 cm^{-2}. If we use the degassing rate after one year, 6×10^{-11} mb, the rate would be 2 % of the upper limit or about 1.2×10^4 molecules cm^{-2}. The degassing rate from Rosina is on par with the upper limit from the BepiColombo rate. Although the degassing rate from BepiColombo appears to be correlated with the temperature of the various spacecraft parts on long time scales (Fraenz et al., 2023), there is too much scatter in the data at any given heliocentric distance to define a dependence on temperature.

2.5.2. Outgassing estimates for Starship

All spacecraft outgas material, especially water, due to exposure to the harsh space environment. As described in Schläppi et al. (2010), this outgassing has three phases: (1) desorption of lightly bound water and volatiles to spacecraft surfaces, dominating outgassing in the first few hundred days after launch, (2) diffusion of volatiles from interior regions of the vehicle, dominating outgassing beyond the first few hundred days, and then (3) decomposition of spacecraft surface material from the space environment (destruction of material via UV, micrometeoroids, etc.), dominating after long times. During the desorption phase, the outgassing is primarily in the form of water, which is found to exponentially decay with a time constant of many 10's of days (~30 days as suggested in Figure 3 of Schläppi et al. (2010)).

Table 11
Estimated Degassing of water from VIPER.

Reference	Degassing Rate molecules/s	Avg. Column Abundance (cm^{-2})
Fraenz et al.; Bepi Colombo	1.4×10^{16}	3×10^4
Schlappi et al.; Rosetta	$1.4 \times 10^{16} - 7 \times 10^{17}$	$3 \times 10^4 - 6 \times 10^5$

Consequently, it is then expected that the Starship lander will outgas water and other volatiles during its many-day stay on the Moon. Assuming that Starship will land on the Moon within a few weeks after launch, the lander will still be in the early desorption phase of outgassing. It is also noted that this outgassing is the thermal emission of volatiles from surfaces both exposed and inside the lander, and not from planned methane-oxygen fuel releases (that creates water) and other planned release activities like airlock releases, etc.

The degassing rate of the Starship lander is currently unknown. However, the outgassing rate can be bracketed by considering outgassing measured or modeled from other vehicles. For example, in examining the water ions produced in the vicinity of the space shuttle, Paterson and Frank (1989) derived a shuttle water outgassing rate of $\sim 2.5 \times 10^{22}$ molecules per second. For a shuttle surface area of ~ 1860 m^2, this rate corresponds to a near-shuttle outflux of 1.3×10^{19} m^{-2}-s^{-1} and a near-shuttle water density, n, of $\sim 2.6 \times 10^{16}$ m^{-3} (2.6×10^{10} cm^{-3}) assuming a water release velocity of ~ 500 m/s consistent with a T~ 300 K surface (as was also assumed in Paterson and Frank (1989)). This number density value can be considered a 'high outflux' case.

The shuttle fuselage had a height of 56 m and a diameter of 8.7 m and is similar in size to the 50-m tall and 9 m diameter Starship vehicle. These bodies are approximated as cylinders, with Starship having an exposed surface area of ~ 1400 m^2. Besides the fuselage, the shuttle also has approximately 324 m^2 of exposed area on its wings, which herein is approximated as 4 triangles areas (top and bottom of 2 wings) with a triangle base of 9.1 m and triangle height of 18.2 m. The outside surface area of the Starship is about 1400 m^2, or 75 % that of the shuttle.

Consider now a more moderate water outgassing case as was measured by Rosetta. The Rosetta spacecraft had a set of three instruments specifically designed to measure cometary atmospheres. However, these instruments also could sense spacecraft outgassing (Schläppi et al., 2010). Specifically, Rosetta's Comet Pressure Sensor (COPS) was placed on a 0.25 m boom from the spacecraft, with the COPS 'nude' gauge providing almost 4 π viewing from this vantage point (Schläppi et al., 2010). COPS measured neutral gas density and the values were then converted to a pressure assuming a reference temperature of 293 K. Early in the mission (first 20 days), COPS measured an outgassing pressure above 2×10^{-9} mbar, corresponding to a near-spacecraft density of n $\sim 5 \times 10^{13}$ m^{-3}. This density will be considered the 'medium' case. After 7 years the pressure

dropped to 3×10^{-11} mb, and the near spacecraft water density was 5×10^5 cm^{-3} at an assumed temperature of 150 K.

It is noted that the Rosetta near-vehicle water density is nearly a factor of 520 lower than that of the shuttle values. The extreme difference in outgassing values may be associated with the shuttle surfaces being fully immersed in the atmosphere while sitting on the launch pad, including being exposed to local weather. This exposure to weather will also apply to Starship. In contrast, the Rosetta spacecraft was protected from the harsh terrestrial environment. The ion outgassing measured during cruise phase on Bepi-Colombo ranged from about $10^5 - 10^9$ cm^{-2} s^{-1} and was uncorrelated with heliocentric distance. The outgassing rates appear to be correlated with temperature of the solar panels. We will use the Bepi Colombo high rate as our "low" rate for the Starship.

Finally, Figure 3 of Schläppi et al. (2010) also presents pressure values from the Midcourse Space Experiment (MSX) (Uy et al., 2003) for comparison. MSX included sensitive optical systems and a set of contamination instruments to assess degradation of the remote-sensing hardware (Huebschman, 1996). MSX was specifically designed with low outgassing materials which also underwent a thermal bake-out (Huebschman, 1996). Obviously, such surfaces were not exposed to the weather, and we thus consider MSX in the class of low outgassing spacecraft. Schläppi et al. (2010) noted that the outgassing from MSX was about a factor of 5 below that of Rosetta. Thus, we can scale by a factor of 5 from the medium Rosetta outgassing case to obtain the low number density case of n $\sim 10^5$/cm^3.

We can then apply these high, medium, and low outgassing scenarios to Starship. Table 12 shows estimates of the outgassing rates for these three cases. The velocity v is the thermal velocity of water emission from a surface with T~ 297 K. The variable F is the outflux of water per unit area. The total water outgassing rate, dn/dt, is obtained by multiplying the outflux rate, F, over the Starship exposed cylindrical area of ~ 1400 m^2. The outgassing mass rate is obtained by multiplying dn/dt by the mass of a water molecule (3×10^{-26} kg).

The total water outgassed over a 6 day period in the high (shuttle-like) case is close to 300 kg. This estimate is comparable to the shuttle values in Paterson and Frank (1989) who found that the space shuttle outgassed ~ 500 kg of water during an 8-day mission. They point out that the quoted outgassed mass is only from thermal outgassing processes and not related the additional water

Table 12
Starship outgassing rates for Shuttle-like, Rosetta-Initial (R-High), Rosetta-7th year (R-Medium) and BepiColombo-cruise (BC-Low) outgassing scenarios.

	n_0 (cm^{-3}) [1] average	v (m/s)	F (cm^{-2}s^{-1})	dn/dt (molec/s)	dm/dt (kg/s)	dm/dt (kg/6 day)	N(cm^{-2}) average
Shuttle	<3600	500	1.3×10^{15}	2.5×10^{22}	7.5×10^{-4}	390	2.8×10^{10}
R-High	<6	360	1.7×10^{12}	2.4×10^{19}	7.2×10^{-7}	0.4	1.2×10^{7}
R-Medium	<4	360	1.2×10^{12}	1.7×10^{19}	5.1×10^{-7}	0.26	8.5×10^{6}
BC-Low	<1	360	2.3×10^{10}	3.2×10^{17}	9.6×10^{-9}	$5. \times 10^{-3}$	1.6×10^{5}

[1] n_0 is the number density at the surface.
[2] n is the exosphere number density.

outgassed by engine and thruster firings and planned released activities. We expect that lunar outgassing rates will be less than the Shuttle rate.

Analogous to the discussion in Section 1.1 and Eq. (4), the average column density in an area of radius R is estimated to be $N_{exo} \sim (dn/dt\ \tau_{exo/}\ /(2\pi R^2)$ where R is the maximum range of the water molecule ejected at 45° angle relative to the local lunar surface (154 km for 500 m/s) and τ_{exo} is the average water hop time in the exosphere ($\sim$450 s at 500 m/s). The total number of molecules making a single hop within the volume is $n_{total} = dn/dt\ \tau_{exo}$. Because the starship is vertical, the molecules initially directed toward the surface will be adsorbed onto the regolith within 0.2 s, thus the total degassing rate is divided by two for the average densities. The column density within 100 m of the Starship due to downward-directed molecules is 570 cm^{-3}. The molecules that reach the surface within 100 m of the Starship represent 14 % of the total outgassed molecules. Thus the Shuttle-rate flux into this area is 3.5×10^{21} s^{-1} and the lunar surface area is 3.1×10^8 cm^2. The rate divided by the surface area within 100 m radius is about 10^{13} cm^{-2} s^{-1}, thus a monolayer of water would build up within a couple of minutes. As discussed in Section 2.6, the surface water deposit will desorb, possibly as H_2 (Starukhina, 2006), over multiple lunar days to create a secondary lunar exosphere.

There are two populations of atoms within 100 m of the Starship: those that directly hit the surface within this region, as discussed above, and those that flow through this region. The average column density directly hitting the lunar surface within 100 m of the Starship represents a column of 10^{13} cm^{-2}. The average number density in is region due to this source population is about 2.6×10^6 cm^{-3}. The molecules that flow through this region and do not directly hit the surface within this region represent a column abundance of 2×10^{14} cm^{-2}. The average column densities due a Starship-outgassed water cloud for the four scenarios are listed in Table 12.

While we do not know which scenario applies to Starship, the fact that both the shuttle and Starship are exposed directly to weather on the launch pad suggests the possibility of a relatively high outgassing rate for Starship closer to the shuttle-like values in Table 12. Both Rosetta and Bepi Colombo outgassing values were measured in deep space. The Bepi Colombo outgassing rates were seen to be corre-

lated with the spacecraft temperature as a function of instrument activity and orientation with respect to the Sun.

2.6. Comparisons to the temporary exosphere created by the Starship landing plume

As described in Prem et al. (2020) and Farrell et al. (2022, 2024)), a lander will eject volatile gases, including water, as it decelerates toward the lunar surface. These ejecta plume gases will embed into the regolith along the landing path creating a human-made volatile deposit that will outgas over time to create a local exosphere. The outgassing source will be strongest in regions near the landing site, where the largest fraction of the plume gases is deposited onto the surface. For example, when considering a 1.2 T Chang'E 3 class landing scenario, Prem et al. (2020) found that the surface deposit of water from the exhaust plume had a peak value in the deposit (exceeding a monolayer) in a 2 km $\times$ 2 km region about the landing site (see Figure 3 of Prem et al., 2020).

Farrell et al. (2024) recently examined the possible water deposit formed during a Starship landing. Starship will use a liquid methane/liquid oxygen propulsion system creating an exhaust plume of 45 % water. Assuming an Apollo Lunar Module-like descent path for Starship (as was done in a hypothetical scenario presented in Farrell et al. (2024)), a possible plume-generated water deposit mass of $\sim$75 T could form that would be deposited over the last 400 km of the landing path. About 14 T of this water would be deposited in a relatively small area: In the last 8 km of the landing path.

This plume-created surface water deposit will then desorb over multiple lunar days and will create a temporary lunar exosphere. In the first lunar day, the amount of water desorbed from a plume deposit in the polar region was derived from Monte Carlo modeling to be about $\sim$70 % of the total water adsorbed onto the surface (for a desorption activation energy of 0.5 eV as shown in the 'adsorbed' curves in Figure 4 of Prem et al., 2020; Figure B1 of Farrell et al., 2024).

For the 14 T of surface water within 8 km to a Starship polar landing site, this 70 % desorption-associated loss corresponds to a release of about 10 T of water into the exosphere over the first lunar day. This loss gives rise to a time-averaged water desorption rate of dN/dt $\sim$1.4 $\times$ 10^{23}/s.

For a polar surface temperature of ~140 K, the bounce time, τ_{exo}, is 310 s, and the maximum bounce range, R, is nearly 80 km. Thus, the number of water molecules found in a volume of $3R^3$ is $n_{tot} \sim dn/dt * \tau_{exo} \sim 4.3 \times 10^{25}$, the average exospheric density, $n = n_{tot}/V \sim 4 \times 10^4/cm^3$ and an average column density, $N_{exo} = n * 2R \sim 6 \times 10^{11}/cm^2$.

We note that this calculation only addresses a water source from the deposit within 8 km of the Starship polar landing location, assuming a LM-like landing scenario (altitude profile and lander pitch angle). We did not include water sources from deposits located beyond 8 km downrange of the lander. Thus, the plume-related density values derived above can be considered lower bounds that can be used for comparison with other outgassing sources.

3. Conclusions

Table 13 summarizes the outgassing from the various transient anthropogenic sources considered above. The dominant source remains the possible water deposit associated with the Starship landing plume. However, outgassing from the Starship itself is also relatively large.

For highly localized source (i.e., "point" sources with source dimensions much less than the bounce radius), the densities will have progressively increasing values reaching peak values close the source (e.g., see Figure 5 of Paterson and Frank, 1989 and Figure 3a,b in Prem et al., 2020). Estimates of these peak values within 100 m of a localized source can be obtained assuming that the source is emitting gas at all angles at a rate, dn/dt, where n is the number of atoms emitted by the source per unit time integrated over the area of the source. The sources emit into a half sphere of 2π steradians, but those molecules that land within 100 m of the source are those emitted upward into a fraction of a sphere, Ω, equal to to 5.9×10^{-4} of the 2π steradians. The atoms reach the height, H, at which the upward velocity is zero. The time to reach this height, τ_{up} is v_0/g and the height is $[v_0\tau\text{-}g\tau^2/2]$. The column abundance is

$$N = \Omega(dn/dt)(2t_{up})/A,$$

and the surface number density is N/H, and A is $\pi \times 100^2$ cm^2. These are the atoms that land within 100 m of the source.lists the order-of-magnitude estimates of the exospheric density in locations close to the various local sources, assumed to be within 100 m. For the backpacks, the estimate is for one backpack. There will almost certainly be two astronauts within the 100 m region considered, doubling the density. However, in the time of flight of the atoms, the astronauts will have moved outside of the 100 m region, halving the estimate. Thus the estimate in Table 13 is reasonable. Since the length of Starship is ~50-m, the point source approximation in deriving the 100-m density likely breaks down and a geometry-specific calculation is required (for example, the location at the top of vertical Starship is only 50-m from the edge of the 100-m half-sphere). However, the approach herein provides a lower bound to the Starship density value at 100-m.

In Table 14, dn_{total}/dt is the source rate integrated over the area of the source (i.e the backpack area, the rover area, etc.), and N_{col} is the average column abundance. We find that the near-source exospheric density values are large for all sources except the rover, and would affect surface mass spectrometer instruments designed to measure the native lunar atmosphere at a few particles per cubic centimeter. The exosphere column of water within 100 m of the astronaut can be as high as $\sim10^{13}$ cm^{-2}, with a surface number density of up to $\sim10^6$ cm^{-3}. This is near a collisional atmosphere which follows the astronaut and is short lived. This conclusion is backed up by the Apollo experiences: As noted in Stern (1999), during lunar daytime, the Apollo Cold Cathode Gauge Experiments (CCGE) and Lunar Atmosphere Composition Experiment (LACE) both experienced constrained and contaminated daytime measurements. Column abundance of water due to outgassing from the rover depends critically on the temperature of the gas, which we assume is relatively warm, 297 K. Colder gas will create a denser exosphere confined near the rover. Estimates of surface number density assume a Chamberlain exosphere (Chamberlain and Hunten,

Table 13
Summary of anthropogenic sources for an averaged temporary lunar atmosphere.

Source	Average Column Density (cm^{-2})	Exospheric Density[1] (cm^{-3})	Dominant Species	Observation period
Backpacks	$< 2 \times 10^{10}$	$< 1.3 \times 10^3$	H_2O	Astronaut EVA
Airlocks	3.5×10^9 (O_2) 10^9-10^{10} (N_2)	< 740 (O_2) $< 1 \times 10^3$ (N_2)	O_2, N_2	Impulsive Releases
Mining [2]	$3 \times 10^8 - 1 \times 10^{10}$	~ 120–1.8×10^3	H_2O	Mining Operations
Trash [3]	$< 8 \times 10^8$; $< 1 \times 10^9$; 7×10^8	< 83; 0.3; 130	CH_4, CO_2, CO	Conversion Operations
Rover	$3 \times 10^4 - 6 \times 10^5$	< 0.1	H_2O	While Present On Surface, T=297 K
Starship [4]	$< 2. \times 10^7$	< 6 (avg) $< 6 \times 10^6$ (local)	H_2O	While Present On Surface
Starship Plume Deposit [5]	6×10^{11}	10^4 (avg)	H_2O	Many Lunations

1. Average exospheric density within a regional volume defined by a single hop.
2. Technology specific value assuming a drill extraction process. 3. Technology specific value assuming a trash-to-gas conversion process. 4. Excludes Shuttle Rates.
5. Assumes a Starship decent trajectory similar to the Apollo 11 LM descent.

Table 14
Estimates of the Near-source Local Exospheric Density from 'Point' Sources.

Source	dn_{total}/dt (molecules s^{-1})	Vcos θ (m/s)	τ (s)	n_0 (cm^{-3}) Surface number density at 100 m from SC]	N_{col} (cm^{-2})[1]
Backpacks H$_2$O	$<4.8 \times 10^{21}$	360–430 T=294–300	640	$< 7 \times 10^5$	$<6 \times 10^{12}$
Airlocks[2] O$_2$ & N$_2$	2.1×10^{20}– 3.5×10^{22}	290–416 T=294	480 (O$_2$) 514 (N$_2$)	$\sim 4. \times 10^4$ (O$_2$) $<6. \times 10^6$(N$_2$)	$\sim 2 \times 10^{11}$(O$_2$) $<3 \times 10^{13}$ (N$_2$)
Mining[3] H$_2$O	1.3×10^{20}–3.3×10^{21}	200–300 T=90–200	246–370	$5. \times 10^4 - 8 \times 10^5$	$6. \times 10^{10} - 2 \times 10^{12}$ T=90; 200 K
Trash[4] CH$_4$,CO,CO$_2$\	CH$_4 < 2 \times 10^{21}$ CO$<7 \times 10^{20}$	550 400 330 (T=585 K)	680 688 408	$<2 \times 10^5$ $< 2 \times 10^5$ $< 7.5 \times 10^3$	$<2 \times 10^{12}$ $< 9 \times 10^{11}$ $<2.5 \times 10^{10}$
Rover H$_2$O	4×10^{16}	500	620	6	$<5 \times 10^7$
Starship[5] H$_2$O	2.5×10^{22}	500	620	$<5 \times 10^7$	$<2 \times 10^{14}$

1. N is the column abundance in the exosphere measured vertically from the lunar surface.

2. Gas is deposited within 100 m of the source into a quarter sphere. 3. Technology specific value assuming a drill extraction process. 4. Technology specific value assuming a trash-to-gas conversion process; assumes a 4 man crew.

5. Based on Shuttle values.

1987). The column abundance from incineration of trash is large, assuming that the gas is not captured for use. Our calculation of the column abundance from mining of ice is conservative and could well be much higher. Gas release from airlocks may be less than calculated herein for more modern airlocks with reclamation of most of the air.

We can now answer a question posed in the introduction: Are these near-object densities high enough to create a collisional gas? To answer this question, we have to compare the gas collision time, τ_c to the molecular bounce time, τ_{exo}. If $\tau_c < \tau_{exo}$, then indeed the molecules will likely collide during their 'bounce'. The density threshold for collisions, n_c, in the case for water (with a molecular collision cross section of $\sigma = 5 \times 10^{-19}$ m^2) is $n_c > 1/(\tau_{exo} v \sigma) > \sim 1 \times 10^7$ cm^{-3} for v = 500 m/s and $\tau_{exo} \sim 400$ s). Examining Table 14, we find that the gas densities are below this threshold at 1 km but exceed this threshold at 2.6-m. Thus, the various point sources give rise to a collisional gas in close to their source. However, the collisional gas cloud with a near source temperature at the surface release temperature is expanding outwards and reaches a boundary between collisional and collisionless (i.e., an artificially created exobase) just inward of 1 km. Future work can be done expanding upon our simple 'formula' approach herein by performing detailed simulated modeling of the local atmospheres as was done in Prem et al. (2020).

For a sensitive mass spectrometer deployed on the surface during a Starship landing and placed in the vicinity of Starship, water outgassing from Starship, rovers, airlock releases, etc., would create local daytime water atmospheres that would greatly exceed the value of the local native water exosphere even in regions near PSRs. Farrell et al., (2015, 2019) found that the PSRs could be sources

of a regional water exosphere and topside water influx (from the crater floor to crater topside regions) due to crater floor icy-regolith erosion by sputtering and impact vaporization. Exospheric densities in the region could be between 0.04–10/cm^3, depending upon the process (sputtering, impact vaporization, impact ejection) and the form of the water (gas and ice). The exospheric values from the natural polar crater sources are far lower than the anthropogenic-created outgassing water levels, but they are more extensive, whereas exospheres from anthropogenic sources are localized.

Even after Starship departs the lunar surface, objects left behind like rovers, will continue to outgas at high levels to alter the detection of the environmental exosphere by mass spectrometers. As noted by Schläppi et al. (2010), outgassing levels will exponentially decrease with a 1/e decay time of ~30 days. Assuming a similar outgassing decay rate for landed systems left behind, it would take about ~410 sunlit days in order to have the outgassing density levels decrease from 10^7/cm^3 to ~10/cm^3 so that a search for the natural exosphere can commence. However, even after this time, there still may be outgassing from the lander plume deposit, which is the largest anthropogenic source. The most important sources of anthropogenic exospheres are backpacks, airlocks and the Starship. Trash and mining operations are difficult to assess at this time, but could be large as human habitation commences. The upper limit on a water exosphere for mining ice is comparable to the other important sources. Outgassing of rovers depends on the temperature of the rover, which also depends on what instruments are operating. Our estimates are first approximations of the order of magnitude of the effects.

4. Summary

The largest source of anthropogenic gas to the exosphere is the landing plume. The column abundance resulting from each of backpacks, airlocks, Starship lander, mining and trash disposal, respectively, produce exospheres at least one order of magnitude less than that from the landing plume. However, the sum of these sources produces half again the amount of gas as the rocket plume. Thus the efflux from twice the number of astronauts, with their resultant sources, would produce an exosphere comparable to one rocket plume.

It has recently been suggested to fly a mass spectrometer in orbit over the polar regions Greenhagen et al., 2022). The calculations herein suggest that when the spacecraft with the mass spectrometer drops to an altitude below $\sim$80 km and passes within $\sim$150 km of the landing site, strong water, oxygen, nitrogen, and carbon/hydrocarbon signals may be detected associated with outgassing from various landed systems. In this regard, orbital mass spectrometers may provide a tool for assessing the impact of these temporary anthropogenic atmospheres on the natural environment. Such orbiting mass spectrometers not only provide new science but can take on a new role as environmental impact sensors. We also recommend that the astronauts deploy mass spectrometers on the surface far from anthropogenic sources to monitor the native lunar exosphere in comparison with the anthropogenic exosphere near human habitation.

CRediT authorship contribution statement

Rosemary M. Killen: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Benjamin T. Sprague:** Writing – review & editing, Investigation, Formal analysis, Data curation. **William M. Farrell:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rosemary Killen reports financial support was provided by NASA Solar System Exploration Research Virtual Institute. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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